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REVIEW

A SURVEY OF THE PRESENT STATUS OF VACUUM MICROELECTRONICS

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Abstract—"Vacuum state" technology appears ready for a comeback in microelectronics form, after years of domination of solid state devices. It will do so, however, based on the developments fostered by solid state technology, which has made available, during 30 years of uninterrupted progress, very sophisticated micromachining techniques, in a large variety of materials, that can be used to advantage for the new developments. Central to "vacuum state" microelectronics is the availability of efficient "cold cathodes", i.e. of electron sources that do away with thermionic electron generation, which would be incompatible in many ways (temperature, power requirements) with microelectronics. Field emission of electrons is used instead; and it is curious to note that the basic idea on which vacuum microelectronics is founded, namely to produce electron emission by the use of "points" or tips that locally enhance electric field, dates to 1961, i.e. exactly to the time when the IC era was just beginning. Evidently, little attention was paid to the proposal by the technological community, perhaps totally absorbed at that time by the exploding interest in semiconductors. A few scientists, however, and particularly C.A. Spindt of SRI Int., liked the idea first proposed by K. R. Shoulders, also of SRI Int., and quietly but tenaciously developed it, and the first interesting results were obtained. More researchers were attracted, and finally the technology turned into something that appears very promising. This paper presents the current state of the technology. After reviewing the basic structures, and some information on the physics of field emission, the "Spindt cathode" and its many variations are examined in detail. Several of the many proposed alternatives to the Spindt cathode are successively reviewed, including that using a *p–n* junction biased into avalanche breakdown, which appears at present the most promising after the Spindt cathode. Turning then to practical applications, those concerning the use of the vacuum microelectronic technology for the realization of cathode emitters are first examined, with reference in particular to their use in displays, which appear the closest to industrial exploitation at this time. More complicated applications, such as complete vacuum microelectronic triodes and IC's are successively considered, and the problems that up to now have hindered the achievement of successful results in this area briefly examined. Finally a comparison is attempted between vacuum state and solid state devices.

1. INTRODUCTION

In the last few years the electronics community has witnessed a renewed interest in vacuum devices. It was at the end of the 50's that vacuum tubes (except for the very special area of high power at high frequency, where they still dominate) started their decline; a decline that continued steadily, to the point that no one, up to three or four years ago, would have considered their return as having even the slightest chance. No one, that is, except a few imaginative scientists, who thought that the exceptional development of the technology, achieved in the meantime, could be used to advantage for a revival of "vacuum state" in microelectronic form.

Microelectronic "vacuum state" devices, in fact, have potentially a number of remarkable advantages with respect to the presently much more popular "solid state" counterparts:

Electrons move in vacuum much faster than the fastest charge carriers in any solid, including GaAs and InP; and in addition their velocity does not experience any "saturation", a common fact in solids in general and specifically in semiconductors, due to the interference of the medium. As a consequence high frequency behaviour will not be limited, as in semiconductor devices, by carrier transit time but, rather, by parasitic capacitances[14]. Thus frequency performance up to several 100–GHz and higher seems achievable[30,59,60].

The effects of temperature on performance are essentially non existent in vacuum devices, simply because there is no medium to cause the usual temperature effects in semiconductors, such as increased lattice scattering (which lowers mobility) or bulk carrier generation/recombination (making semiconducting properties fade to the point of total extinction). Thus useful performance should be possible up to temperatures (e.g. 500°C) presently unthinkable of in solid state devices[14,65].

Again because there is no medium to be damaged, either temporarily r permanently, radiation effects should be negligible in vacuum

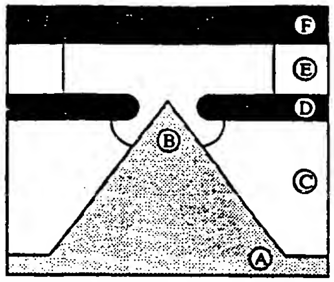


Fig. 1. Vacuum microelectronic tube structure. A is the substrate, B the field emitter, C and E the insulating layers, D is the grid and F the anode. [From Ref. 63.]

devices, and up to four order of magnitude better resistance is expected[65].

In addition to this, the present availability of microfabrication technologies, allowing vacuum devices to share with solid state devices similar micron-size features (a fact which contributed in determining the 60's decline of vacuum tubes[34]), have fostered the revival of vacuum state.

Although many problems, as we shall see in a moment, need still to be solved, these advantages, and the feeling that they are within reach, attract the attention of more and more researchers and scientists. An *International Vacuum Electronics Conference* was held for the first year in 1988, and is now (1991) at its fourth edition. The well known IEEE magazine *Transaction on Electron Devices* has published many articles on the subject, and also most of the papers presented at the Conference. The *International Electron Device Meeting (IEDM)*, a traditional forum for microelectronic devices, dedicates special sessions to Vacuum Microelectronics.

Most of the research activity is presently taking place in the United States. Some activity, possibly more than is known to the technological community[46], is also being developed in Japan, and very recently[7] a MITI-sponsored research initiative was announced. In Europe, GEC and Philips are actively engaged, and some work has also been developed at Siemens and in France; efforts are also going on in the CIS.

In the following, after a short description of the basic structures, the physics behind the operation of vacuum microelectronic devices are reviewed and an attempt is made to assess the present status of the technology.

2. BASIC STRUCTURES

The structure on which vacuum microelectronic devices are based is, in principle, that of the vacuum triode: a "cathode" generates electrons, the flow of which is controlled by a "grid" before they are collected by the "anode", to which the accelerating potential is applied.

The classical triode has however a fundamental incompatibility with microelectronics: the thermionic cathode; indeed, the high temperatures and high power dissipation it requires for satisfactory operation are not acceptable in any microelectronic structure. As a consequence an *alternate* source of electrons was absolutely necessary for vacuum microelectronics to become a viable technology.

As far back as 1961, Shoulders proposed[70] for the first time the use of a "field emitter" as the electron source, consisting of sharp points of suitable material which, because of their sharpness, could locally enhance the electric field originating from an externally applied voltage, to the point of causing electron emission.

Actually, electron field emission was already a well known phenomenon, but of no practical use (at least in microelectronics) because of the very high voltages it required. Since 1928 Fowler and Nordheim[27] had studied its physics and determined the governing equation (the same, by the way, describing charge movement in today's EPROM/EEPROM devices).

The novelty of Shoulders' idea was simply to use very sharp points for local field enhancement, which made low voltage operation possible. A "cold" electron emitter was thus available, at least in principle, and vacuum microelectronis suddenly became a viable proposal. The resulting structure is schematically shown in Fig. 1. Real structures will be described in Section 4.

A totally different idea is to use a p–n junction biased into avalanche as a low voltage "cold" electron source. In such a device electrons in the depletion layer, either existing or generated by impact ionization within the same layer, gain energy from the high field in such a region; and, if the junction is sufficiently shallow, many of them can acquire the necessary kinetic energy to reach the surface and win the surface work function, thus escaping into vacuum.

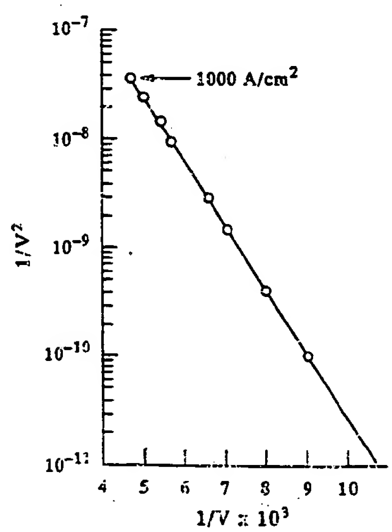


Fig. 2. A typical "Fowler–Nordheim" plot. [From Ref. 79.]

A very large number of experiments have been carried out, particularly during the last three or four years, in order to assess the feasibility of vacuum microelectronic devices based on the two basic ideas for a cold cathode described above. Many variations of these ideas have been proposed, and a few quite different than the two mentioned. We will review them in Section 4.3; now however, for a thorough understanding of the phenomena, a brief description of their physics is in order.

3. THE PHYSICS OF FIELD EMISSION

The movement of electrons across an energy barrier Φ, under the effect of an electric field E, is described by the Fowler–Nordheim (F–N) equation:

$$J = AE^2\Phi^{-1}\exp(-B\Phi^{3/2}/E), \qquad (1)$$

in which A and B are constants (only approximately however; in reality they have a weak dependence on field) and J is the current density.

For a given structure, i.e. for specified materials and geometries, eqn (1) can be written in terms of current I and voltage V as:

$$I = MV^2\exp(-N/V),$$

in which M and N (in the limits of the approximation mentioned above) are constants. This equation in turn can be written:

$$\log(I/V^2) = -N/V + \text{const.}$$

which indicates that a semi-logarithmic plot of I/V^2 vs $1/V$ produces a straight line. This kind of diagram, rightfully named a "Fowler–Nordheim diagram", is very popular with researchers in the cold electron emission field, since it allows, based on measurement results, to quickly reveal if the emitter they are studying does indeed follow the F–N law. If the plot they obtain is not a straight line, this is taken as an indication that emission is not purely of the F–N type, and that additional mechanisms intervene in the phenomenon. A typical F–N plot of this kind is shown in Fig. 2.

In the applications of our present interest, the energy barrier Φ of eqn (1) is the so called "work function", measured in eV, which is characteristic of the material being considered and is physically interpreted as the effect of the electrostatic forces exerted upon an electron attempting escape by the positive charges of the remaining atoms and by the other electrons within the escaping cloud.

Introducing coefficient values (as in Ref. [11]) and neglecting certain minor effects, (1) can be written as:

$$J = 1.54 \times 10^{-6}E^2\Phi^{-1}\exp(-6.83 \times 10^7\Phi^{3/2}/E). \qquad (2)$$

Here J is in A/cm^2, E in V/cm and Φ in eV.

In eqn (2) the dominating term is the exponential, and as a consequence J increases very quickly with increasing field E and with decreasing work function Φ. To give this statement quantitative evidence, let us evaluate (2) in situations of possible applications. This requires estimating the electric field E at the tip, which is not easy, since the exact mechanisms of the emission are not clearly understood. Spindt[77], under specific assumptions, has estimated indirectly for E a value between 1.74×10^7 and 8×10^7 V/cm.

We will use the value $E = 2 \times 10^7$ V/cm (or 2 kV/μm), which is perfectly adequate for our purpose. Assuming also $\Phi = 4$ eV, one gets from (2):

$$J = 2.1 \times 10^{-4}\ \text{A/cm}^2.$$

If, at this work point, we increment the electric field by 25%, i.e. to $E = 2.5 \times 10^7$ V/cm, we get:

$$J = 7.75 \times 10^{-2}\ \text{A/cm}^2.$$

In percentage values:

for $\Delta E/E = 25\%$ we get $\Delta J/J = 3.7 \times 10^4\%$.

Turning now to the effects of Φ, let us calculate what happens in the vicinity of the same work point of $E = 2 \times 10^7$ V/cm and $J = 2.1 \times 10^{-4}$ A/cm^2 if we change Φ by -25%, from 4 to 3 eV. We get:

$$\Delta J = 4.04\ \text{A/cm}^2.$$

Percentage wise:

for $\Delta\Phi/\Phi = 25\%$ we get $\Delta J/J = 2 \times 10^6\%$.

Having thus established that electric field and, much more markedly, work function, have important effects on current density, we will now examine to what extent these factors can be controlled.

Field value can be affected by:

the externally applied voltage;
the distance between the electrodes to which voltage is applied;
the "shape" of the emitter.

The applied voltage has obviously to be kept as low as possible, possibly in the 10 (or less) to 50 V range, in order to insure compatibility with other electronic components.

The distance cannot go below limits of compatibility with the available microelectronic fabrication technologies, and will therefore be of the order of 1 μm. In any case the resulting field must remain safely below the dielectric strength of the insulating materials used in the structure; and this, for even the purest materials, is in the range of 10^6 V/cm (or 100 V/μm). For example, in SiO_2, dielectric strength is about 4.10^6 V/cm[47]; and in Si_3N_4 about 10^7 V/cm[79].

The third factor, i.e. the "shape" of the emitter can therefore be used to advantage, in that, everything else being the same, the use of sharply pointed emitters will locally increase field strength and therefore the emitted current. This was in fact the new idea in Shoulder's proposal.

The "field enhancement factor", defined as the ratio between the enhanced electric field at the emit-

Table 1. Work function values and melting temperature of some materials [from Ref. 74]

Material	(eV)	Melting temperature (°C)
Ag	4.7	960.5
Al	3.0	659.7
Au	4.8	1063
Ba	2.52	850
Bi	4.1	271.3
C	4.7	>3500
Ca	3.2	810
Cd	4.1	320.9
Cs	1.8	28.5
Cu	4.1	1083
Fe	4.7	1535
Hf*	3.6	
Hg	4.5	−38.87
Ir*	5.4	
K	1.8	62.3
La*	3.3	
Li	2.2	186.0
Mg	2.4	651.0
Mo	4.3	2620
Na	1.9	97.5
Nd	3.3	
Ni	5.0	1455
Pb	4.0	327.4
Pt	6.0	1773.5
Rb	1.8	38.5
Sr	2.1	800
Ta	4.1	2850
Ti*	4.09	
Th	3.4	1845
W	4.52	3370
Zn	3.3	419.47
Zr	4.1	1900
LaB_6^*	2.74	
NdB_6^*	4.57	
TaB*	2.89	
TaC*	3.14	
ThO_2^*	2.55	
TiC*	3.35	
ZrB*	4.48	

*From Ref. [30].

ting tip and the average field in the cathode–anode gap, is given by the expression[84]:

$$\beta = kh/r,$$

where k is a constant and h and r the height and the radius of the emitting tip.

Although an exact evaluation of β is difficult[12,77,84], its order of magnitude can be as high as a few hundred; experimental measurements[12,61] indicate values ranging from 50 to 500. This of course indicates how important is the effect of using sharp tips as the emitters.

The work-function Φ depends essentially on the material being used as the emitter. Table 1, reported from Ref. [74], supplies work-function values for several materials used in the past for the fabrication of thermionic cathodes, many of which appear suitable also for field emitters. For both applications, in fact, a low value of the work-function favours electron emission.

Much can be learned from the incredibly high (even by to-day's standards) amount of information available on materials for thermionic cathode application, described in detail in excellent review papers[5,100]. Additional data can be found in Refs [30,67,52,75]. Attention must be paid however to the fact that the operating conditions are, in field mitters, markedly different than in thermionic emitters; and specifically that the operating temperature in the latter case is much higher than in the former. As a consequence certain physical phenomena (such as diffusion in solids and other temperature-stimulated effects) of which advantage can be taken in the case of thermionic emission, are negligible in field emitters.

A very important aspect, which obviously affects the choice of materials, is also that, during its operation, the tip can be subjected to energetic bombardment by ions which always form in a vacuum tube due to the presence of extraneous residual gases, resulting both from imperfect vacuum conditions and from outgassing of the materials within the device[9]. This phenomenon was of course present also in thermionic valves, but in that case the structure of the cathode was sturdier than the very fine tips we are now considering.

There is however much more to consider in addition to work-function values.

Just to mention one factor, the temperature characteristics of the material must be compatible with the application. In general, work-function values decrease with increasing interatomic distance of the material, which lowers interatomic forces, thus making electron extraction easier; for the same reason however melting temperature is lower and volatility higher[74,100]. Caesium, for example, has a low work-function value (1.8 eV), but at the same time a very low melting temperature (28.5°C), making the use of this material difficult in our kind of application.

As an additional example, it has been shown[8] that, in certain conditions, Ti-coated emitters perform better compared to a Ta-coated emitters, in spite of the two materials having equivalent work functions; and this is attributed to the ability of Ti to produce, using similar fabrication techniques, geometrically more suitable (sharper?) points. Obviously then, the ability of the material of being properly machined, chemically or otherwise, plays an important role.

It should also be pointed out that, when the emitting tip is formed in a semiconductor material, the emitting mechanism becomes more complex than determined by pure Fowler–Nordheim emission[35,84] although a heavily doped n-type silicon emitter tends to behave very similarly to a metal emitter[63].

In addition to temperature stability, additional physical properties, such as workability and processing compatibility with the remainder of the fabrication technology, are important aspects to be considered.

We will show in the next sections that the research activity in field emitters has covered so far many aspects of the physical realization of the emitters themselves; and a sort of competition has been

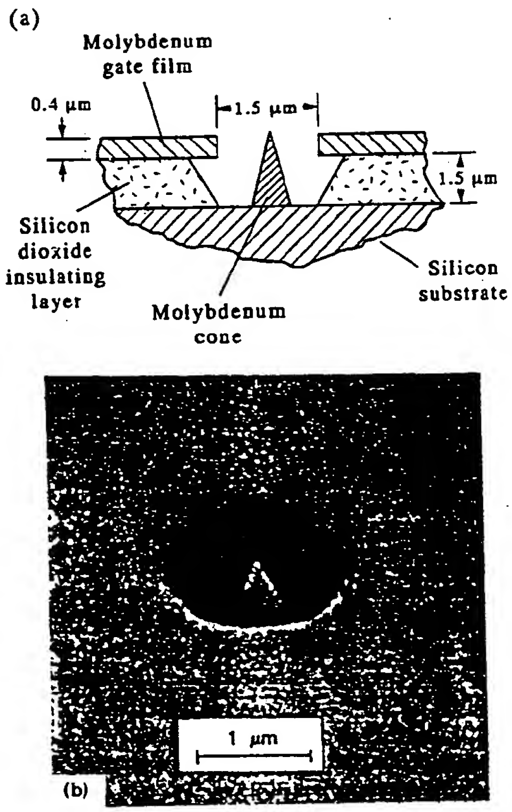


Fig. 3. The "Spindt" cold emitter. (a) The basic structure and some critical dimensions. (b) A SEM micrograph of the device. [From Ref. 77.]

started concerning the achievement of the sharpest tips or of the easiest fabrication process. Comparatively little effort has been dedicated to the emitting materials; indeed, in certain cases, the choice of the material appears determined more on the basis that it allows a simplified, or more familiar, fabrication process, rather than improved performance.

It is an indication of this that, of the many materials listed in the work-function table above, only very few have been investigated up to now; and that, in general, these are not the materials which, in view of the low work-function they exhibit, would appear most interesting.

This leads to the conclusion that, along with the research on structures and fabrication technologies, a serious effort is badly needed on materials; and that, as a consequence, significant improvements can legitimately be expected in this area, as some recent efforts in this direction show[23].

4. THE FIELD EMITTING STRUCTURES

The field emitting structures appearing most interesting will now be described. In order to correctly assess the value of the results achieved up to now, some kind of a reference is needed. This can be obtained from the performance of "classical" thermionic emitters, and is represented by the current density obtained from those considered particularly efficient. In Beck's review paper[5] the value of 1 A/cm^2 is considered a practical limit; more recently[95], up to 50 A/cm^2 have been obtained in specially constructed thermionic cathodes.

The field emitting structures will be here grouped in three categories:

- the "Spindt cathode" and its variations;
- the avalanche diode cold emitter;
- miscellaneous structures

4.1. *The "Spindt cathode" and its variations*

4.1.1. The "Spindt" cathode. The "Spindt cathode", named after C. A. Spindt of SRI International, who initially proposed it in the late 60's[76] and has since worked on its improvement, is undoubtedly the most actively investigated structure by many researchers in a large variety of shapes and configurations, and also the one on which the most interesting results have been obtained.

The original Spindt structure is made up of sharp tips of molybdenum each encircled by a metal gate

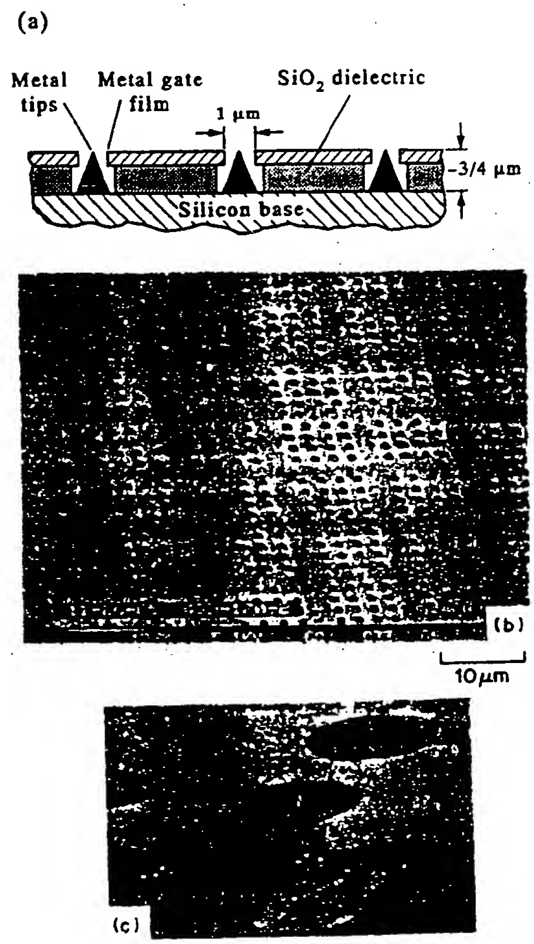


Fig. 4. An example of a "Spindt" cathode. (a) The general schematic. (b) A SEM micrograph of an array of cathodes. (c) A SEM micrograph of a single emitter. [From Ref. 79.]

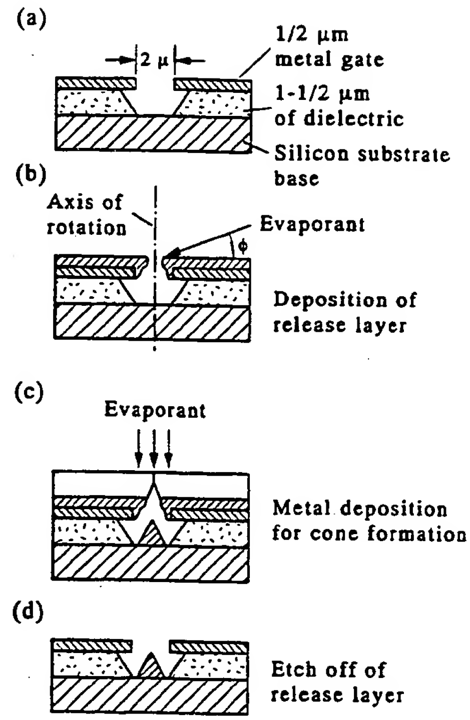


Fig. 5. The fabrication process proposed by Spindt. [From Ref. 76.]

also of molybdenum, as shown in Fig. 3. The structure is built on a silicon base and the fabrication process closely resembles standard silicon processing. The tips are arranged in arrays of various dimensions, as shown in Fig. 4. In the latest realizations[79] very high packing densities have been achieved of up to 1.5×10^7 tips/cm^2 (corresponding to a tip-to-tip spacing of about 2.5 μm); single tip currents of about 10 μA are routinely obtained in arrays of 10,000 tips for a total current of 100 mA, and total current densities of 100 A/cm^2. Higher single tip currents of up to about 100 μA per tip, with densities of 1000 A/cm^2, have been demonstrated, but in smaller arrays (16 tips), due to the need to limit power dissipation of the cathode in the test set-up used.

Spindt has also demonstrated that a "forming" process, consisting of heating the cathode while the tips are under high field stress, enhances the emission current several orders of magnitude for a given voltage.

Another important parameter for a cathode is transconductance, defined as the rate of change of emitted current vs the change in voltage producing it. Spindt[79] has obtained, before "forming", transductance values of 5μS/tip, corresponding, in a 10^7 tips/cm^2 array, to a total transconductance of 50 S/cm^2. This represents three to four orders of magnitude higher than in thermionic cathodes.

These impressive results, in every respect several rders of magnitude better than for thermionic cathodes, are obtained in spite of the use of a relatively high work function emitter material such as molybdenum ($\Phi = 4.3$ eV). The envisaged use of lower work function materials (Titanium Carbide, $\Phi = 3.35$ eV, is one candidate), and the use of forming, should further improve the results and also permit the use of voltages in the order of 30 to 50 V, i.e. compatible with present day microelectronics.

A relatively simple fabrication process is described by Spindt in several of his papers[76,77], and is repeated here in Fig. 5. The process allows easy adjustment for the use of different materials than those shown.

An important feature of a suitable fabrication process should be its ability to produce self aligned cathode-gate structures. In fact the voltage at the grid substantially affects the field at the emitting tip and the overall performance of the device, as demonstrated both by simulations[63] and measurements[77]. As a consequence any asymmetries, inevitably resulting from a non-self aligned process, would produce poor yield and/or performance. The Spindt process, as described in Fig. 5, guarantees self alignment.

The use of wedges (Fig. 6), rather than points, as the basic emitting devices has also been proposed[17,53,55]. Comparative simulations[17,55] shows that wedges with the same basal area as points have significantly reduced emission; however practical reasons, such as the greater capacity of dissipating heat, the possible availability of processing tricks capable of reducing the top radius of the wedge, the better use they make of the available surface, and finally and intrinsically sturdier structure, may make wedge emitters preferable[53].

4.1.2. Emitters using "composite" materials. Due very probably to the apparent simplicity of the Spindt structure, and also to the present-day familarity with technological processing in general, many researchers have attempted reproducing the structure with different methods and/or mateirals.

An interesting approach is that originally proposed by Cline[20] at G.E., and recently actively pursued by researchers at the Georgia Institute of Technology[19,20,21,26,44] and by others[47,81]. In this approach so called "directionally solidified eutectic composite materials" are used for the fabrication of structures that closely resemble those of Spindt, and

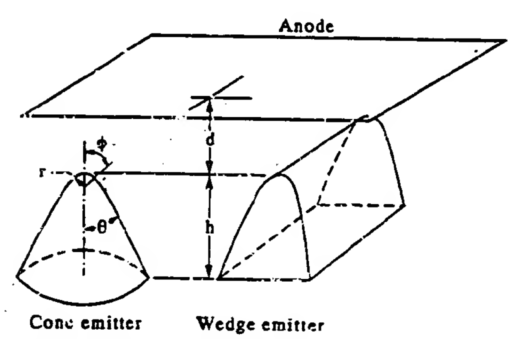


Fig. 6. A cone and a wedge shaped emitter. [From Ref. 17.]

Fig. 7. Pointed fibers in composite material. [From Ref. 19.]

that potentially lend themselves to even higher tip densities. These materials consist of an oxide matrix containing a dense (over 5×10^7 fibers per cm^2 of transversal cross-section) crowd of fibers of various materials, with very fine diameters (as low as 0.2 μm). The base materials are metal oxides, while the fibers are crystalline materials, in various combinations[26]: UO_2–W, ZrO_2–W, Gd_2O_3–Mo; other materials are YSZ-W[20] (yttria-stabilized-zirconia matrix with tungsten fibers), and a NiCr matrix with TaC or NbC fibers[21]. They are fabricated[20,26] by mixing the various materials in well controlled proportions and successively zone-melting and directionally solidifying the mixture in induction-heated furnaces. The procedure is such as to allow segregation of the crystalline material in very fine and parallel (but randomly spaced) fibers, very close to each other. The ingot thus obtained is then sliced in wafers, with the fibers perpendicular to the wafer surface. The process[21] continues by exposing and pointing the fibers (Fig. 7) using suitable etchants, and then by electron-beam evaporation of an alumina (Al_2O_3) insulating layer and a superimosed molybdenum layer serving as the

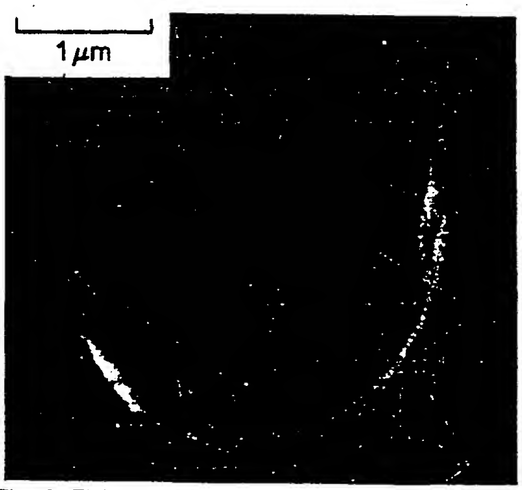


Fig. 8. Finished cold cathode structure in composite material. [From Ref. 19.]

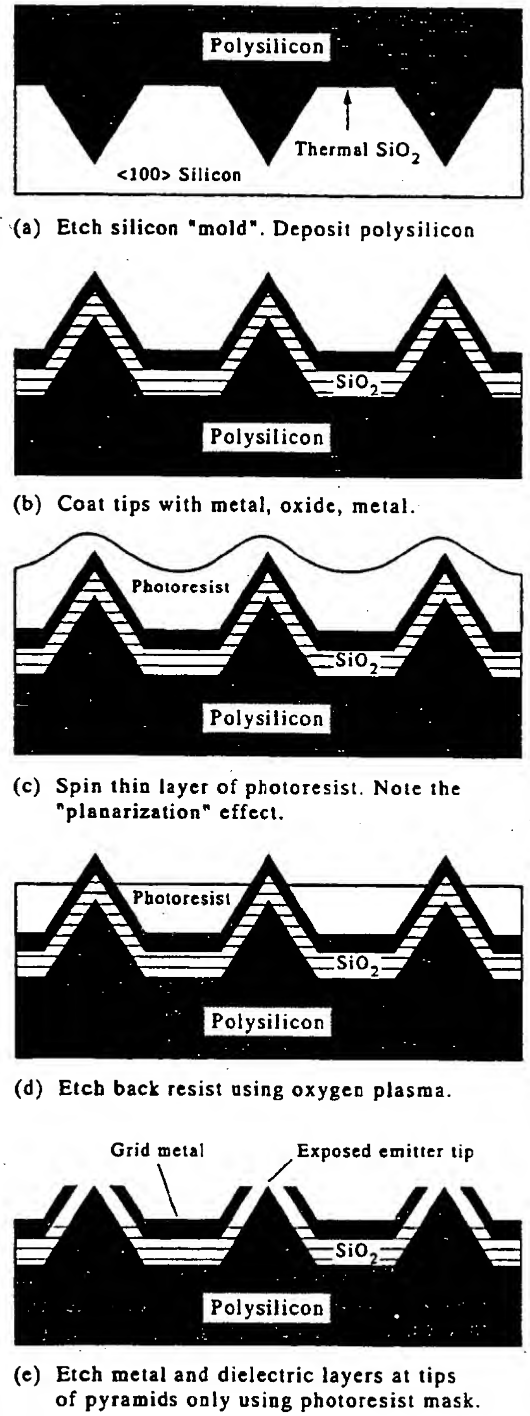


Fig. 9. An example of a Si-based cold cathode fabrication process. [From Ref. 72.]

grid conductor. By taking advantage of the shadowing effect of the points during E–B evaporation, circular holes, centered on, and self-aligned with, the pointed emitters, are produced in both the insulating layer and the grid layer. The final structure (Fig. 8) is indeed very similar to the Spindt structure of Fig. 3.

Fig. 10. Gated structure resulting from the process of Fig. 9. [From Ref. 72.]

4.1.3. Emitters using Si-technology. "Lateral" emitters. Particularly long is, obviously, the list of attempts based on silicon technology, enriched by additional degrees of liberty made available by the possibility of using materials and processes acceptable for this structure, but incompatible with, or of no interest in semiconductor devices.

As the situation appears at this point, not one of

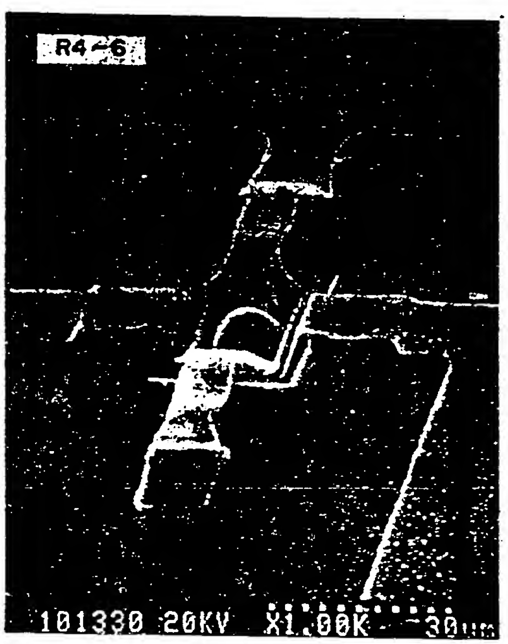


Fig. 11. Complete vacuum microelectronic triode. [From Ref. 63.]

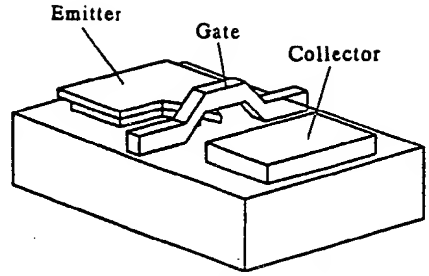


Fig. 12. "Lateral" structure for a vacuum microelectronic triode. [From Ref. 11.]

these alternative structures has come even close to the performance achieved by Spindt and summarized above: demonstrated current densities are generally several orders of magnitude lower. In spite of this, new ideas bearing promise of technology improvement have been proposed, and deserve attention. Some of them will be briefly described here.

The structures to be described include simple emitters, i.e. cathode-gate structures, as well as complete cathode-gate–anode structures.

Several silicon-based self aligned processes have been developed [40–43,52,57,72,73,106]. We will show here, Fig. 9, the process originally proposed by Gray and Greene[33] and described by Sokolich *et al.*[72] and by Alder *et al.*[1] of Hughes, which produces the gated device for Fig. 10.

This process is particularly simple (only one masking operation is necessary) and well known processing steps are used, none of them appearing critical. Dimensions of individual structures and distances between electrodes, although very small, can be easily controlled: the aperture of the gate electrode and the gate to emitter gap are of the order of 1 μm. This should allow low voltage operation, and indeed the onset of emission has been measured to be at below 10 V. Current density, however, is of the order of 0.5 A/cm^2, i.e. three orders of magnitude below Spindt's results, which indicates that substantial improvements are needed.

An interesting "micro-cavity integrated vacuum tube", as their authors name it, is described by Orvis *et al.*[63,64,65] of the Lawrence Livermore Lab. Its process uses standard solid-state device formation techniques, but requires precautions due to the complexity of the structure. The resulting device, Fig. 11, is a complete triode, with internal spacings in the micrometer range, which lends itself to the creation of individually evacuated and sealed microtubes (whereas the other structures generally require ouside evacuated cavities to hold them). Prototypes of the structure have been realized, but certain process steps are rather complex and need further development effort.

Another class of devices are the so called "lateral" types, in which complete triode structures can be easily fabricated horizontally (as opposed to the "vertical" structures presented up to now) using well

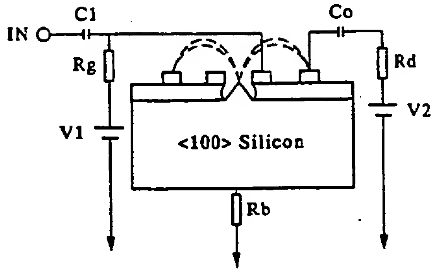


Fig. 13. "Mixed" structure: cathode and gate electrodes resemble those of Fig. 1, but the anode is in the same plane as the gate. [From Ref. 31.]

known processing steps[11,15,32,45]. A typical resulting structure is sketched in Fig. 12.

The advantage in this case is essentially of a very simple and familiar process for a complete triode structure; however structure density (i.e. devices/cm^2) is obviously lower than in the vertical case. Also performance, measured as well as simulated[16], is poorer.

A "mixed" structure, in which the cathode-gate electrodes are vertical but the anode is in the same plane as the gate (Fig. 13) has also been proposed[31], based on silicon technology. It is interesting to note that a device based on this structure was historically the first to show that gain could indeed be obtained from vacuum microelectronic triodes (1986).

4.1.4. The improvement of emitter efficiency. We will now examine research efforts having a somewhat more restricted extent than those described above. These works aim to the solution of particular aspects of a more general problem, such as obtaining a special structure or examining a certain material or fabrication process. In spite of this limitation, some of this work is of great value, since its results can become part of the total fabrication process and thus contribute to the advancement of the technology.

One particularly important topic is the sharpness of the points, since this affects the "field enhancement factor", the importance of which has already been discussed in Section 3.

Although the precise dimensions of the emitting area and its exact position in the tip are still debated issues[40,41,46,54,62] all experiments indicate, and simulations confirm[17], that emitting efficiency increases as tip dimensions decrease. All researchers therefore have given this problem the attention it deserves, by devising suitable fabrication methods and techniques.

The original Spindt process[54] achieved molybdenum tips of about 500 Å in diameter. At about the same time similar dimensions were obtained using silicon[84]. Obviously when silicon (both mono- and polycrystalline) is chosen, the enormous experience available with this material becomes available; indeed, very often this material is chosen because of the familiarity with it, and not because it exhibits special advantages in vacuum devices. Excellent papers on the application of Si-based fabrication techniques for the realization of sharp points and field emitters have been published[2,6,13,41,57,80,86,99].

A method, originally proposed by Smith *et al.*[71] has been technologically developed by Marcus *et al.*[55,56], and allows the formation of silicon tips of Å radius. This method takes advantage of the build-up of a stressed zone at the Si-oxide interface when a silicon surface presenting high curvature is oxidized at about 1050°C or below. In the area of high stress, i.e. at the tip, the oxidation rate is lower than elsewhere[22], thus causing a sharpening of the tip. Fig. 14, a TEM image of such a tip, shows the result that can be obtained.

The process can be combined with the chemical reduction of tungsten esafluoride by silicon[12,56].

$$2WF_6 + 3Si = 3SiF_4 + 2W,$$

obtained in a CVD reaction chamber.

The tungsten resulting from the reaction deposits on the Si tips, while the SiF_4, being volatile, is eliminated with the carrier gas. With this simple process tungsten coated silicon tips can be easily fabricated, in an application where the higher resistance to harsh environments of this material can be advantageous.

Other methods for obtaining Å diameter silicon tips have been developed and are being combined into the frame of a process capable of producing complete emitter structures[43].

4.2. The avalanche diode cold emitter

The emission of electrons from a silicon junction biased into avalanche breakdown was first observed and measured by Burton in 1957[108]. After this,

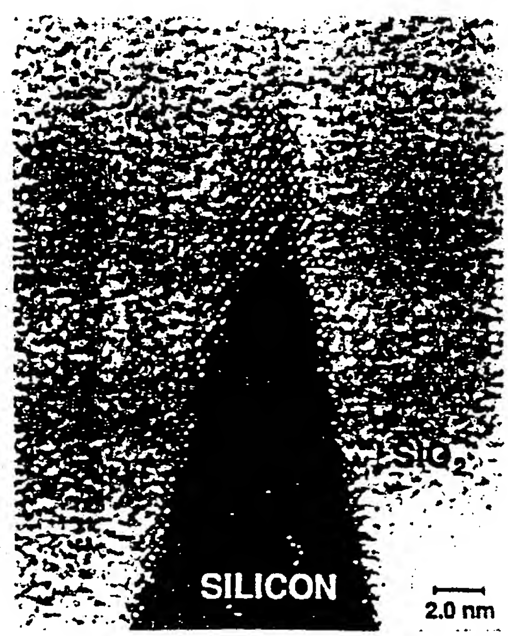


Fig. 14. TEM view of a very sharp Si tip. [From Ref. 53.]

many other researchers investigated the phenomenon, their interest being essentially of a better understanding of the phenomena in p–n junctions biased into breakdown.

The first practical use of this type of electron emission was found in the early 70's, when it was used in EPROM and EEPROM devices: the electrons generated by a junction into avalanche where stored into an isolated oxide island or "floating gate", thus affecting the threshold voltage of a MOS transistor, and realizing a "permanent" memory.

The idea of using the phenomenon for the realization of "cold cathodes" was proposed by Van Gorkom and Hoeberechts of Philips in 1980[91]; and these two researchers have since worked on the subject, obtaining most of the results[38,92,93,94,95,96]. More recently other researchers have joined in[24].

The structure presently used by Van Gorkom and Hoeberechts is shown schematically in Fig. 15. A p-type layer is epitaxially grown on a heavily doped p^+ substrate (for low series resistance), which will serve as one of the terminals of the diode; on this p^- layer an n^+ region is obtained by standard diffusion techniques, which is used for the electrical contact to the other terminal of the diode. A p^+ region is then obtained within the p^- region by ion implantation, and on top of this an n^{2+} region, is also obtained by ion implantation, but at very low energy, so that it remains very shallow (about 10 nm). Finally an insulating layer (SiO_2 or a combination SiO_2/Si_3N_4) is deposited, on which a "gate" or grid contact is formed.

Doping levels and geometries are designed so that the p^+–n^{2+} junction, which is the diode active region, breaks into avalanche at lower reverse voltage than the p–n^+ region under the contacts. During operation the diode is reverse biased above the first, but below the second breakdown. Under the effect of the high electric field that builds up in the depletion region, electrons present there gain kinetic energy; and a fraction of them do so to the point of winning the obstacles represented by scattering in the top layer (which, to make the transition easier, is built very shallow) and by the work function of the material, thus escaping into vacuum.

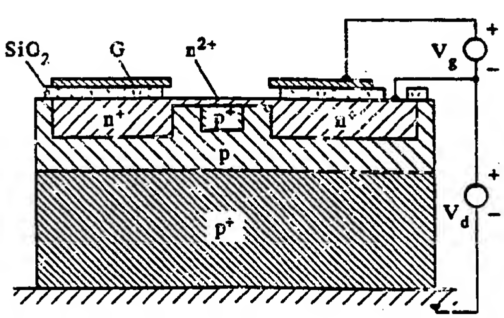


Fig. 15. Structure of the "avalanche diode" cold emitter. [From Ref. 95.]

Many shapes, such as circular, linear, annular and meander can be used for the active region, depending on the application and the value of the emitted current.

The most recent resutls[96] indicate that current densities as high as 8000A/cm^2 can be realized, which is much higher than for the best Spindt cathodes. These results, however, were obtained by using a monoatomic layer of caesium deposited on the active surface of the structures, in order to take advantage of the very low work function of this material; and the use of caesium, due to the poor stability of this material (re. Section 3), requires many precautions, such as very high vacuum (below 10^{-11} torr) in order to eliminate all oxidizing gases, and extreme cleanliness.

An additional consideration is that the emitted current is a small fraction of the total current through the diode: the best result today is 8%, but more commonly only 3–4%. Correspondingly, only a small fraction of the total power consumed is useful power, the remainder being lost as heat. Getting rid of this heat without causing unacceptable temperatures in the silicon substrate poses an upper limit on the total useful current that can be obtained.

In comparison, the Spindt cathode and its variations are in a better situation, since power dissipation in the cathode is determined only by the emitted current. For example, if 100 mA of useful current were to be produced (a level routinely obtained by Spindt[79]) with the avalanche diode, a total current in excess of 1.25 A (assuming optimistically 8% as the efficiency) would have to be run across the reverse biased diode; and since the diode avalanche voltage is between 6 and 9 V[95], the resulting power dissipation would reach 7–11 W, a level certainly difficult to handle. In conclusion, applications of the avalanche diode cold cathode are restricted to those cases where relatively small emitted currents (e.g. 10 mA) are needed. This situation may change drastically if the efficiency is improved, and researchers[97,98] are aiming at this through the use of a potentially more suitable material, such as GaAs, which has a higher bandgap and should therefore allow transferring higher energy to electrons in the depletion layer. Also, alternative diode structures, such as the PIN and the Schottky, which appear more suitable to solve certain problems, are being investigated[87,90]. So far however experimental evidence of significant improvements has not been provided.

Van Gorkom and Hoeberechts have not apparently attempted to exploit potential application of their device at microwave frequencies. As a matter of fact, the only application for which their avalanche diode structure has been used, and with very successful results, is that of electron source for use in cathode-ray tubes, which will be briefly described in Section 5.

4.3. Miscellaneous structures

We will now briefly describe some structures, most of which, at the time of this review, have not been

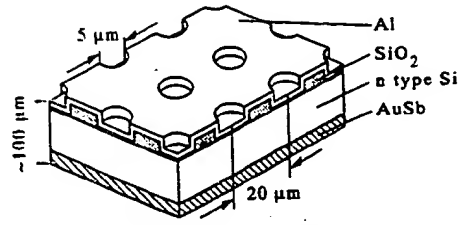


Fig. 16. Honeycomb MIS cod cathode structure. [From Ref. 103.]

developed to the point of providing useful results; since however some of them represent a significant deviation from the approaches described up to now, and are certainly potentially interesting, it is worth giving them some attention.

The first structure to be described is the so called "Negative Electron Affinity (NEA) cold catode"[36,37]. This device was first proposed in 1966[29], and consists of a p^+–n junction made in a wide band-gap semiconductor such as GaAsP, having both sides very heavily doped (the p side more than the n side); the p side must be very thin (less than 1 μm) and is coated with a low work function material such as caesium. In these conditions, a NEA situation is obtained, i.e. electrons injected into the p-side by forward biasing the junction have little or no energy barrier to win, and can freely escape into the vacuum which is to be maintained on the p side of the junction. As observed by Geppert[29], the device behaves as an n–p–n transistor, in which vacuum takes the place of the n-type collector. The critical region of this device is obviously the p^+ side surface, its state and defect density needing special attention in order to effectively realize the NEA condition, without which a satisfactory electron emission will not take place.

Metal–Insulator–Metal (MIM) or Metal–Insulator–Semiconductor (MIS) structures, in which one or more of the layers must be properly selected and/or treated so that electron emission can take place when a relatively low voltage is applied between the two external layers, have been proposed.

One of these uses as the emitting electrode a "porous" silicon layer, which is obtained when a highly doped p or n type silicon surface is subjected to electrochemical anodization in concentrated hydrofluoric acid[101,104]. This layer is found to consist of 10^{10} to 10^{13} pores per cm^2, each having from 10 to 100 Å diameter; at the interface between porous and bulk silicon, extremely sharp points, with similar density, are formed. Both the density of pores and their diameter can be controlled during the process. The porous silicon layer is subsequently oxidized and a metal layer is deposited, which operates as the collector. When a voltage is applied between the substrate and this metalization, an electron current is collected at the metal layer; specific experiments have shown that these electrons move in the vacuum of the pores and that the I–V characteristic follows Fowler–Nordheim statistics[104]. Electron currents as high as 250 A/cm^2 have been collected.

No indications in the mentioned references are given as to the means for making the electron current available to the outside of the structure.

The idea of producing similar minutely dispersed and pointed microstructures is being pursued with various approaches.

In one[48,69,85], cylindrical "tubules", i.e. hollow microtubes, about 0.4 μm in diameter and 10–100 μm in height, are formed using certain biologically derived surfactants called phosphatidylcholines. These, after electroless coating by metal to make them electrically conductive, could be used as the emitting structures.

An additional approach is to take advantage of the electron tunneling phenomenon. Structures used with this aim consist of a very thin (one or few atomic layers) insulating region sandwiched between two conductive layers, one of these, exposed to vacuum, being similarly thin. If a d.c. voltage of the correct polarity is applied to the two outside layers, sufficiently high as to extract electrons from the negative electrode and to transfer to them sufficient energy, these electrons will "tunnel" through the insulating and the thin, positively biased layer, and will be emitted into vacuum. These structures, as many others in this type of applications, need a "forming" process before they reach maximum efficiency, consisting in general of a period of time during which a voltage, often higher than the normal operating voltage, is applied to them; it is believed that during this phase minute points form in the emitting

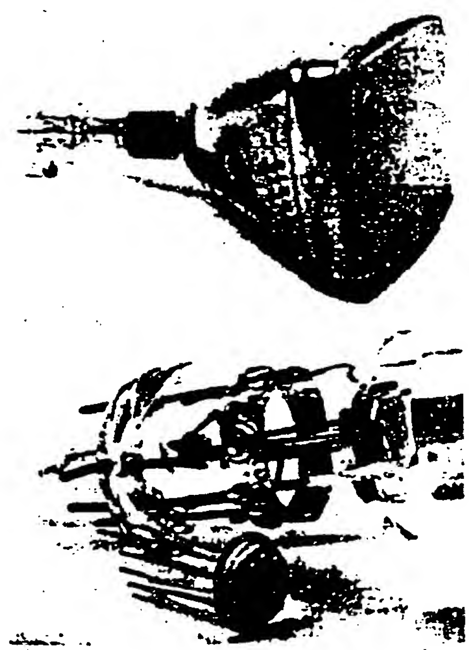
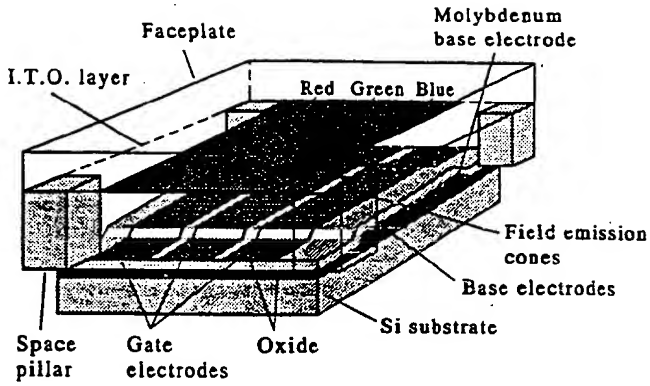


Fig. 17. Small television tube using a Si avalanche cold cathode as the cathode. [From Ref. 96.]



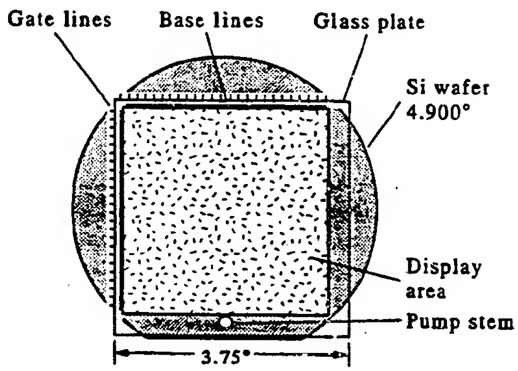


Fig. 18. Vacuum fluorescent color display using a Spindt field emitter as the cathode. Top: general cutaway of the display. Bottom: display assembly structure. [From Ref. 78.]

electrode, at which preferential emission takes place because of the locally enhanced electric field.

Yokoo *et al.*[102,103] propose a honeycomb MIS structure as in Fig. 16, built on low-resistivity n-type silicon, and consisting of regularly spaced regions either of very thin SiO_2, or of mono-atomic thickness of single crystal alumina (Al_2O_3), covered with a very thin aluminium layer obtained by sputtering. Outside the "active" areas the insulator is standard SiO_2 topped by a standard Al layer. Emphasis up to now has been on the development of the technology, in particular of the very thin insulating layer; emission characteristics are being studied.

A MIM structure is used by Yankelevitch *et al.*[101] of Russia. In this case an oxynitride–silicon ($Si_xN_yO_z$) insulating layer, of 10^2–10^4 Å thickness, is sandwiched between two (unspecified) metal layers, the top layer being 100–200 Å thick. It is very likely that in this structure the governing phenomena are both more complex and less understood than simply tunneling. The authors estimate that, during the forming process, some 10^6–10^8 "channels of increased conductivity" per cm^2 are formed within the insulating layer, which as a result becomes partially conductive. When the operating voltage, about 10 V, is applied, a d.c. current flows and electron emission takes place. Quoted results indicate an emission current density of about 10 mA/cm^2 and an efficiency of 1%.

The latter results are encouraging; undoubtedly however further investigations are necessary in order to fully understand the phenomena that take place within the insulating layer under high field stress, so that they can be industrially controlled and consistently reproduced.

5. APPLICATIONS

We will now examine some applications of vacuum microelectronics to real working devices, either present (albeit preliminary) or potential.

In addition to the actual physical realization of working prototypes, a great deal of activity has been spent in modelling and simulation, and mention will also be made of some of these efforts.

The applications will be grouped in ascending order of difficulty, as follows:

emitters only (cathodes);
new "discrete" active devices, or VMFETs;
vacuum microelectronic integrated circuits.

5.1. *Applications as "pure" cathodes*

Since high performance electron cold emitters have been realized, as we have described in Section 4, the easiest and most obvious idea is to use these new devices as a replacement of thermionic emitters. This has indeed been done in existing and technologically

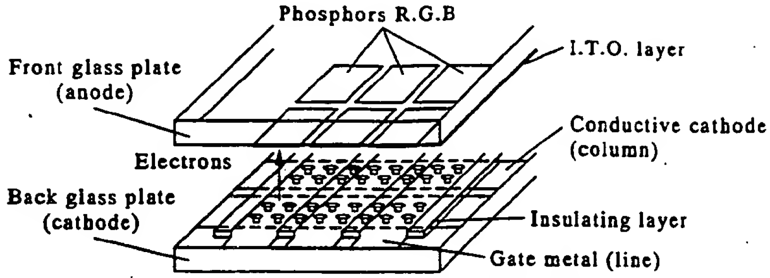


Fig. 19. LETI's fluorescent display structure using field emission. [From Ref. 59.]

mature applications, as well as in more sophisticated and newer devices.

Using vacuum electronics technology for the realization of cathodes does not allow, generally, to take advantage of all its features and in particular of the expected microwave performance; it however permits a direct comparision with well experimented solutions and therefore a valuable assessment of the industrial applicability of the new technology.

Van Gorkom and Hoeberechts[38,95,96] have successfully used their Si-avalanche diode cold cathode as the emitter in an otherwise conventional, small (10 cm diagonal) television tube (Fig. 17).

The verified advantages of such a device are: a significantly lower power dissipation (only 10 mW), allowing the tube to be usable as a monitor in battery operated consumer cameras; instant switch on (no warm-up necessary); a simplification in the electron optics of the tube, since beam modulation can be obtained very simply by applying a low-level (few volts) video signal to the avalanche diode. Excellent performance is reported and no problems of a technical nature are envisaged hindering commercial exploitation[96].

The same authors report the successful use of similar devices in oscilloscopes and electron microscopes; and also suggest[94] that avalanche diode cold cathodes could be used as individually operated multiple emitters in multibeam electron lithography systems, resulting in a speed advantage of such machines.

A much more sophisticated display device using field emitters has been investigated by Spindt *et al.*[78]. The application concerns a vacuum fluorescent color display having the basic design shown in Fig. 18.

The electron source is an array of Spindt cathodes, one for each pixel, realized on a single silicon wafer of 12.5 cm (5 in.) diameter. Each cathode consists of three stripes, one for each basic color, and is addressed in one direction through the molybdenum layer, which is formed into stripes; and in the orthogonal direction through the gate layer, patterned in adjacent groups of three stripes each, one for each of the colors. The size of each pixel is 250 μm square, with a total of 338338 pixels in the complete display. The faceplate of the display is made of glass, the internal face of which is coated with a transparent and electrically conductive indium–tin oxide layer; onto this layer, stripes of the three colored phosphors are deposited, matching in dimensions and relative positions the corresponding stripes in the gate layer. This faceplate is mounted on the cathode so that phosphors are properly aligned to the emitters, but remains separate from them by suitable "space pillars". The entire assembly is finally evacuated and sealed.

In spite of a few problems that emerged during prototype fabrication, the authors feel that the major assembly and processing problems have been overcome, but admit that additional refinements are necessary. This is the least one can expect for a device of such a complexity, involving "wafer scale integration" of a cold cathode, as well as several delicate fabrication and assembly operations.

A much simpler field emission based display structure has been proposed by LETI in France, where it is actively studied. In a recent paper[59] Meyer describes it in detail. The display (Fig. 19) consists of two glass plates, assembled and sealed at close distance (about 200 μm internal gap, controlled by suitable spacers) which produces a very thin (2 or 3 mm) overall structure.

The back plate hosts an array of field emitters, the cathodes and grids of which are arranged in orthogonal stripes, each stripe containing many structures. A pixel of the display is identified by the area corresponding to the crossing of a cathode stripe with a gate stripe, which contains a large number of "microguns", or emitters (about 1000 emitters for a 0.1 mm^2 pixel). Each gate stripe corresponds to a display line; pixel brightness is controlled by applying proper voltages to the various cathode stripes.

The front plate is internally coated with the phosphors, arranged in RGB sequences for color displays.

Anode–cathode voltage is limited to 400 V, safely below electrical breakdown. As described in the artiele, a current of only 0.1 μA/tip, a density of 10^4 tips/mm^2 and up to 80 V of grid-cathode voltage, are sufficient for satisfactory pixel brightness. All of this is well within the capabilities of the available technology, and therefore the approach is very promising. Indeed, after initial current uniformity problems were cured by the use of a thin layer of controlled resistivity silicon under the emitting

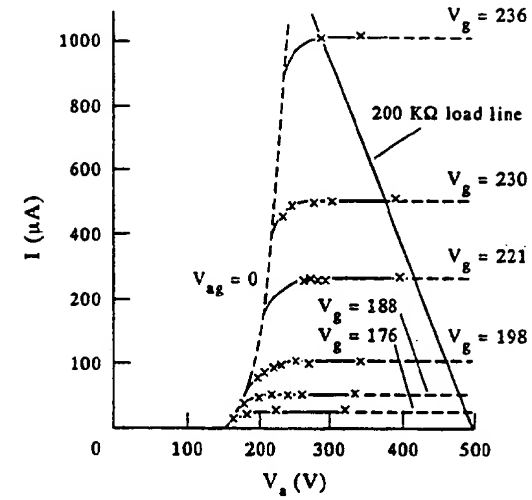


Fig. 20. Output characteristics of a vacuum microelectronic triode. [From Ref. 39.]

structures and by the use of forming, satisfactory 6" monochrome displays have been produced.

These developments in display structures indicate that industrial exploitation of vacuum microelectronics in this field may be very close. This is confirmed by a recent article[46] in the trade press, which suggests that several japanese companies may be close to the commercial introduction of display devices based on vacuum emission.

5.2. Applications as "discrete" active devices

It has been observed[66] that in the early 50's, high performance vacuum tube triodes such as the Western Electric 416 A had been perfected to the point of achieving useful gain up to 4 GHz. This performance however was obtained at the expense of very high mechanical precision: the mentioned tube, in fact, used a grid of 2.25 mm in diameter, mounted only 15 μm above the thermionic cathode; and the grid wires were 7.6 μm in diameter, spaced 25 μm from each other. Mechanical tolerances in grid-cathode and wire-to-wire spacing had to be kept below 10%. Such high precision was on one side difficult to obtain and reproduce; and on the other imposed an almost unsurmountable limit to performance improvement. Similar dimensions and tolerances, on the other hand, are routinely obtained with modern microelectronic techniques, and can in fact be considerably improved. In itself, therefore, vacuum microelectronics has the potential to yield high performance devices, easily producible at low cost.

These considerations notwithstanding, up to this moment (Nov. 1991) not a single really successful result can yet be reported for the vacuum microelectronic triode or FET (which from now on, borrowing the name from Spindt and Holland[39], we will call VMFET) even though meaningful low-frequency amplification has been demonstrated in several cases. Evidently, the difficulties become significantly higher when, from a simple diode, we move on the the realization of the more complex triode structure.

Some of the more interesting attempts will be mentioned later in this paragraph. Before this we will however briefly describe the electrical performance that can be expected for these devices as related to their physical construction, on the basis of a few elementary physical considerations, of computer simulations and finally of measurements performed in some real structures.

Essentially all of the following considerations are made with reference to vertical structures similar to that in Fig. 1, since most of the realizations are based on the highest efficiency emitter available, today, i.e. the Spindt cathode or one of its varations.

5.2.1. Biasing considerations[63]. In a standard vacuum tube, the thermionic cathode generates electrons due to thermal excitation. Electrons are then accelerated toward the anode by the anode voltage, which is more positive than the cathode. A negative voltage (vs the cathode) is applied to the grid; when this voltage is modulated, electrons are more or less strongly repelled, and in this way the flow of current towards the anode is controlled. If the grid is allowed to go more positive than the cathode, some of the electrons will be diverted to the grid, resulting in a cathode-gate leakage that degrades the tube performance.

In a VMFET cathode emission is determined by the high electric field at the emitting site; and electrons, after they are generated, will rush through the grid opening towards the positively-biased anode; and will not, at that point, by affected by the grid voltage. In other words (and contrary to the situation in a standard vacuum tube) the grid cannot affect the flow of electrons *after* they have been generated; rather, it controls the emission itself, by affecting the field at the emitting site.

Again contrary to the situation in a vacuum tube, grid voltage vs cathode must be positive. In fact, if the grid where more negative than the cathode, the anode–grid potential would be higher than the anode–cathode potential; and emission from the grid would become likely, causing an undesirable anode–grid current. A positively biased grid will not cause any significant grid current, because, as observed above, electrons will have acquired such a high velocity that the grid is unable to deviate them.

5.2.2. Output characteristics[39,60]. An example of output characteristics (anode current vs anode voltage) for a vacuum microelectronic triode[39] is shown in Fig. 20.

This figure shows that the triode characteristics closely resemble those of a traditional thermionic pentode, rather than of a triode. This indicates that anode voltage has a negligible effect on the field at the cathode and thus on emission from it, and that field and emission are essentially controlled by the grid voltage. In other words, the grid electrode effectively

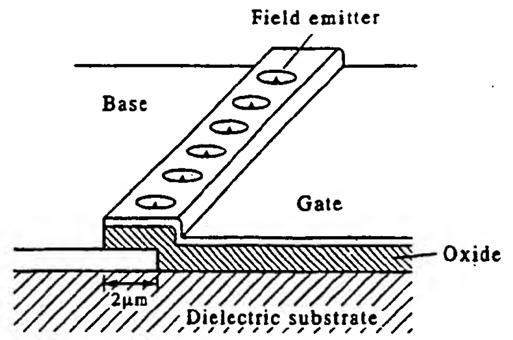


Fig. 21. Cathode structure to reduce gate-cathode capacitance. [From Ref. 39.]

screens the anode from the cathode, as confirmed by computer simulations[42].

Clearly, as the anode voltage is reduced and the $V_a = V_g$ condition is approached, the emitted electrons start being captured by the grid and, as shown in Fig. 20, a boundary is reached. It is to be noted that this may become critical at high voltage, since current in this condition can increase considerably, and the gate electrode may not be able to sustain the corresponding power dissipation.

Output characteristics obviously depend on many parameters: materials, geometries, surface status, etc. Several computer simulations have been made[4,54,82], which however generally take into account only geometrical effects.

5.2.3. Electrical parameters. Output resistance. As Fig. 20 shows, the anode current, above a certain anode voltage and at any given grid voltage, is essentially constant; therefore the output (or anode) resistance:

$$R_a = (\delta V_a / \delta I_a) V_{g=\text{const.}}$$

is essentially infinite.

At the same time, due to the input (grid–cathode) capacitance, the input impedance is relatively low. As a consequence direct output–input coupling will not be possible, and suitable passive coupling circuitry will be necessary. Since these coupling circuits are generally of the pass-band type, a narrow frequency band must be expected for such an amplifier[66].

Frequency response. Due to the high velocity of electrons in vacuum, it can be shown[34,60] that frequency response in a VMFET is not limited by transit time, but by transconductance and inter-electrode capacitance. The relevant relationship:

$$f_T = g_m / 2\pi C_{gc},$$

gives the cut-off frequency f_T as a function of the transconductance g_m and of the grid–cathode capacitance C_{gc}.

Transconductance obviously changes proportionally to the number of emitting sites; and can therefore be easily increased, in a Spindt type cathode, by increasing the number of the emitting points. This however will not improve the frequency response, because C_{gc} will also increase in proportion. Indeed, increasing the size of the cathode beyond certain limits can actually reduce frequency response, because the cathode lateral dimensions should remain below a quarter of a wavelength of the desired operating frequency in order to maintain RF field uniformity across the cathode structure[60].

Improving the frequency response therefore requires increasing g_m while at the same time decreasing C_{gc}. Several realistic possibilities exist, using presently available technology, to obtain these objectives[39], namely:

- increasing the tip density: 2 μm centers have been demonstrated, and 1.5 μm is possible;
- "forming" of the tips could be routinely used to lower operating voltage and increase transconductance;
- low work-function materials or coatings can be used for the emitters;
- using a "wedge" geometry, in place of the cones, would increase the emitting area without a corresponding increase in total area;
- a properly studied cathode layout, such as that shown in Fig. 21, can significantly reduce C_{gc};
- a further reduction of C_{gc} can be gained by increasing the thickness of the oxide separating grid and cathode.

An estimate of the cut-off frequency that can be obtained, if most of the above improvements are implemented, is given by the authors proposing them[39] as about 100 GHz, which would make these devices perform as, or better than, presently available solid state devices.

5.2.4. Experimental results. The first reported test on a complete VMFET structure is that of Gray and Campisi[31] of NRL (the Naval Research Lab.); the structure (Fig. 13), is realized on a silicon substrate, and is a mixed one, with the cathode being a vertical structure of the Spindt type, and both gate and anode laying on the sides of the cathode. From this device, which was actually made up of multiple cells ordered in a multifinger geometry, both voltage and power gain were obtained at low frequency. Considering the early date of the experiment (1986), this was indeed an encouraging result.

Since then, surprisingly, no additional examples can be found in the literature until 1990/91, when additional attempts are reported in two papers, one also from NRL scientists[60] and one of SRI Int.[39], i.e. two organizations that have actively collaborated in this field; and in fact Spindt type emitters are used by both teams, and Spindt of SRI Int. is one of the co-authors in both papers.

In both experiments the VMFETs are realized by externally providing various anode structures for the Spindt emitter, which is mounted in a standard TO5 header base. The resulting structure is then either put in a vacuum chamber or evacuated before electrical testing.

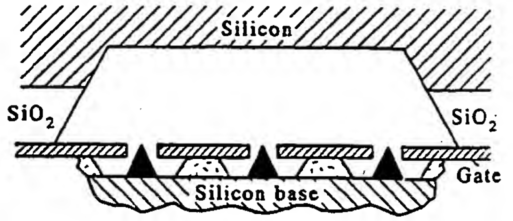


Fig. 22. A realistic structure for a vacuum microelectronic triode. [From Ref. 39.]

In the NRL experiment the anode consists of a 3 in. long, 0.8 cm in diameter (a truly Euro–American set of units of length!) tube. In the SRI paper three different structures are considered, the first of which is very similar to that of NRL (but the cathode dimensions are different). Also the operating conditions and the results are comparable: in both cases an anode voltage of several hundred volts was necessary, with ensuing high power dissipation, and the frequency cutoff was found to be below 1 MHz. In the NRL experiment a low frequency voltage gain of 11 dB is reported.

The remaining two SRI experiments concern much smaller structures.

In the first, the anode consists of a thin plate mounted at 1.25 mm from the cathode and contained in the same TO5 header as the cathode. In spite of the much smaller dimensions, and of the more manageable voltage and power levels, performance remained poor, with a frequency cut-off at about 140 kHz.

The last SRI attempt is an even smaller structure (Fig. 22) which closely resembles what could possibly be an optimum approach: the anode consists of a silicon chip, separately fabricated using standard silicon technology, and successively mounted on the cathode structure, using as a separator an SiO_2 layer purposely grown on the chip and removed in the central area, together with some of the silicon layer; by varying the thickness of the oxide and the depth of the trench, the anode-cathode distance can be chosen within a fairly wide range. Two- and eight μm spacings were experimented at SRI.

Unfortunately this attempt did not measure to expectations, and a fairly quick deterioration in emitted current was observed, attributed by the authors to an apparent increase of the work function; also failure of some of the emitting points was ascertained. These phenomena were attributed to the difficulty of effectively evacuating the structure, due to its small dimensions; and this may have left contaminants inside the device, which were then responsible for the observed phenomena.

It is clear that further experiments and investigations are necessary before any final conclusions can be drawn.

5.3. Vacuum microelectronic integrated circuits

Taken in the ordinary meaning attributed to this expression, vacuum microelectronic integrated circuits should be monolithic circuits including several elementary vacuum microelectronic devices, which, when suitably connected among themselves and to proper passive elements formed on the same substrate, produce specified functions. An even more general approach would be that of a semiconductor substrate on which both solid-state and vacuum-state devices are built, together with passive components, so that advantage is taken of both the two approaches.

These structures can certainly be imagined, and indeed they where envisaged by Shoulders since 1961[70]. Fabrication processes that are in principle suitable to achieve such results have been proposed[106]. It is clear however, considering the difficulties currently encountered in the fabrication of much simpler devices, that formidable problems must be overcome before such structures become a reality. As a consequence, no examples of this kind of IC's have been reported up to now.

Several structures however have been proposed in which the active devices they contain closely interact with the surrounding structures in order to produce a useful function, and they rightfully deserve to be considered true IC's.

The first of these structures is the well known Distributed Amplifier. A VMFET based version of this classical circuit, nicknamed FETRODE, is proposed[50] by Kosmahl of Hughes Aircraft. Its schematic diagram is shown in Fig. 23, with each stage including input and output transmission lines corresponding to "discrete" inductance and

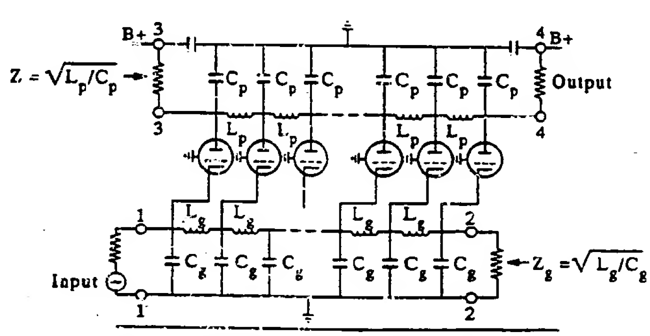


Fig. 23. FETRODE schematic diagram. [From Ref. 50.]

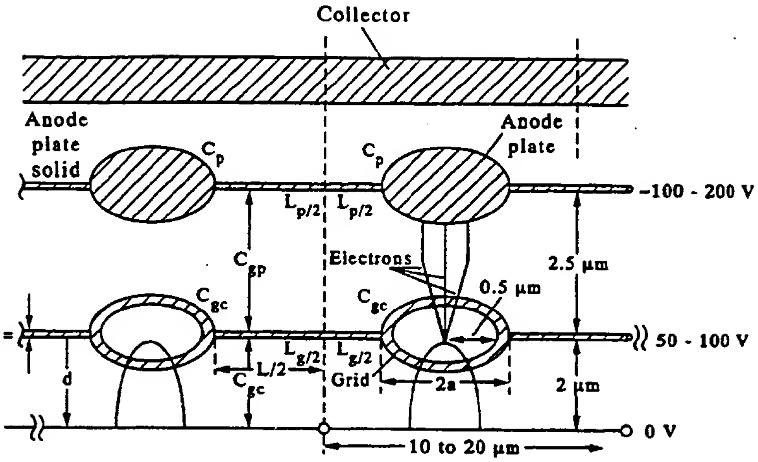


Fig. 24. FETRODE structure. [From Ref. 50.]

capacitance elements intrinsic to the proposed structure. This is shown in Fig. 24, with this correspondence clearly indicated; it is to be noted, in relation to this figure, that a grid structure consisting of very narrow geometry rings, connected by equally narrow strips, and "suspended" above the cathodes, is proposed.

Very fine geometries, down to 2 μm or below, are proposed, which of course does not make the realization of the amplifier very easy. Such a critical structure is however considered necessary in order to drastically reduce the input capacitance of the active devices, which severely affects frequency performance. An analytical evaluation made by the author on the basis of the proposed geometry indicates an improvement in cut-off frequency of approximately one order of magnitude over a similar circuit using MESFET devices, and corresponding improvements in efficiency and bandwidth. An operating frequency range of 10–300 GHz is considered possible.

A "continuous" (as opposed to "discrete") distributed amplifier, originally proposed by Gray and Greene, has been analyzed theoretically by Ganguly *et al.*[28]. The structure of this amplifier is schematically shown in Fig. 25. Both input and output sections are made up of continuous distributed lines; the input section, containing the grid and the wedge-type cathode, is separated from the output section, containing the anode line, by a screen electode which blocks feedback from the output. The operation of this amplifier is very similar to that of a TWA. Electrons move as usual from cathode to anode under the effect of the electric field and the electron beam is modulated by the grid signal. The beam interacts with the output wave, propagating parallel to the wedge emitters, and excites waves in both the forward and backward directions. If the phase velocities in the input and output circuit are identical (which can be obtained by proper design), the forward waves add in phase while the backward waves are out of phase; as a result output waves grow in the forward direction only. The results of the analysis by Ganguly *et al.*, which assumes cathode performance compatible with present results obtained by Spindt, show that for optimum amplifier performance the vertical dimension of the circuit should be in the range of 80–120 μm, which is perfectly compatible with microfabrication technologies, and that a proper design should yield a gain of about 7 dB/cm at a frequency from 50 to 80 GHz.

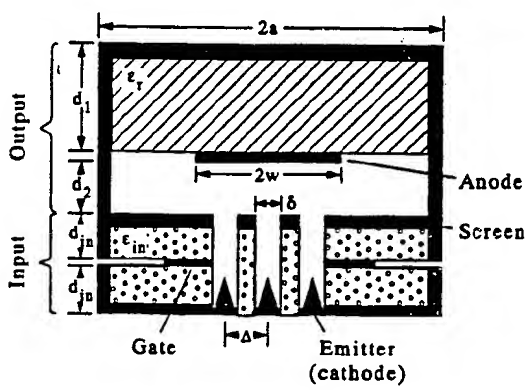


Fig. 25. Continuous distributed amplifier structure. [From Ref. 28.]

A structure very similar to that described above has been studied by McGruer *et al.*[58], who forcesee a realistic possibility of obtaining useful performance up to 1 THz; certain modifications are of course necessary in order to cope with the higher frequency range and with the consequent higher power dissipation.

It is a general need, for all the presented structures to achieve high performance, that the electron source have low specific input capacitance and high specific transconductance. For this reason, Spindt emitters, or variations thereof, have invariably been considered as their cathodes, since these structures have up to now demonstrated the best performance,

particularly in the values of transconductance. Actually still higher performance cathodes are necessary in many cases before the expected results are obtained, and as a consequence many of the improvements proposed by Spindt and listed in section 5.2.3 will have to be achieved for the realization of high performance vacuum microelectronic IC's.

6. "VACUUM STATE" VS "SOLID STATE": ATTEMPTING A COMPARISON

As we have seen, the general consensus is that vacuum microelectronics have indeed the potential to produce higher performance microwave devices than today feasible using solid state devices.

It must be mentioned however that, while the higher insensitivity to high temperatures and to radiation effects of vacuum devices appears unquestionable, doubts have arisen concerning frequency performance[3,25].

One can in fact imagine that forthcoming technology improvements will soon allow routine fabrication of sub-micrometer solid state devices, to the point that the distance to be covered by charge carriers becomes lower than their "mean free path" (about 0.2 μm in GaAs); as a consequence their movement will begin becoming "ballistic", i.e. carrier velocity will be little affected by the medium. Thus what in the beginning appeared as a decisive factor in favour of vacuum devices, where electrons can move freely, would lose any relevance.

In addition to this, one must consider that in semiconductors, due to the presence of positive ions and to the consequent neutralization of electron charges, current flow is not limited by space charge effects; while this is, by contrast, a common fact in vacuum. As a consequence current densities in semiconductors can be orders of magnitude higher, with the same applied voltage, than in vacuum[25]. The effect of this is a lower intrinsic resistance of solid state components, and therefore improved frequency response.

The conclusion is then that solid stage devices, if their critical dimensions are sufficiently small, will maintain their lead in frequency capabilities[3].

The above considerations must be, of course, weighted against the forseeable evolution of vacuum state device fabrication technology: if it will be "simpler" (and this appears as a realistic possibility today), and if current densities can be raised to higher levels (and the latest results by Spindt, as mentioned in Section 4.1, move in this direction), the fact that in vacuum devices the use of larger critical dimensions does not impair frequency performance will certainly be a considerable advantage.

Indeed, as we have seen in the previous sections, on the basis of different models and/or structures, many researchers conclude that vacuum devices can perform usefully up to the THz region[28,50,59,89].

The question is therefore still open, and a wait-and-see attitude is the best choice at this highly evolutionary stage of the technology. In fact several improvements that directly affect frequency performance, such as the choice of a better emitting material (with a lower work function) and newer structures capable of higher current density, can reasonably be expected in the near future.

In any case, if the additional advantages of vacuum devices are considered, one may conclude that there is plenty of application possibilities for these devices to conquer an important position in future electronics.

7. CONCLUSIONS

Varied and intense as it is, the research on vacuum microelectronics has yet to produce working devices, susceptible of real applications. Up to now, and only to a limited extent, this has been demonstrated for vacuum electron emitters, the industrial application of which to displays appears very close[7,38,46]. On the other hand, no clear cut demonstration of useful operation of VMFETs, even at low frequency, has been produced; and the situation appears even less gratifying if we move on to the more complex structures of complete amplifying devices.

This is in a way obvious. Nontheless, the fact alone that many researchers are spending their efforts for the realization of complete structures even at this very early stage of development, testifies of their convincement that the technology will soon produce results.

If we in fact give a closer look at the situation, we realize that many of the problems that up to know have hindered success appear to have been identified; and many researchers world wide are actively tackling them. It is then reasonable to expect solutions to these problems in the next few years. When this happens, the electronic designer will have available one additional family of components which will complement, and certainly not substitute, those available today.

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